

DISCOVERY OF A 1.6-YEAR MAGNETIC ACTIVITY CYCLE IN THE EXOPLANET HOST STAR ι HOROLOGII

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ABSTRACT

The Mount Wilson Ca HK survey revealed magnetic activity variations in a large sample of solar-type stars with timescales ranging from 2.5 to 25 years. This broad range of cycle periods is thought to reflect differences in the rotational properties and the depths of the surface convection zones for stars with various masses and ages. In 2007 we initiated a long-term monitoring campaign of Ca II H and K emission for a sample of 57 southern solar-type stars to measure their magnetic activity cycles and their rotational properties when possible. We report the discovery of a 1.6-year magnetic activity cycle in the exoplanet host star ι Horologii, and we obtain an estimate of the rotation period that is consistent with Hyades membership. This is the shortest activity cycle so far measured for a solar-type star, and may be related to the short-timescale magnetic variations recently identified in the Sun and HD 49933 from helio- and asteroseismic measurements. Future asteroseismic observations of ι Hor can be compared to those obtained near the magnetic minimum in 2006 to search for cycle-induced shifts in the oscillation frequencies. If such short activity cycles are common in F stars, then NASA's *Kepler* mission should observe their effects in many of its long-term asteroseismic targets.

Subject headings: stars: activity—stars: chromospheres—stars: individual(HD 17051, HR 810)—surveys

1. BACKGROUND

Astronomers have been making telescopic observations of sunspots since the time of Galileo, gradually building a historical record showing a periodic rise and fall in the number of sunspots every 11 years. We now know that sunspots are regions with a sufficiently strong magnetic field to alter the local thermal structure, so this 11-year sunspot cycle actually traces a variation in surface magnetism. Attempts to understand this behavior theoretically often invoke a combination of differential rotation, convection, and meridional flow to modulate the global field through a magnetic dynamo (e.g., see Rempel 2006). Although we cannot observe spots on other solar-type stars directly these areas of concentrated magnetic field produce, among other signatures, strong emission in the Ca II H (396.8 nm) and K (393.4 nm) spectral lines. The intensity of the emission scales with the amount of non-thermal heating in the chromosphere, making these lines a useful spectroscopic proxy for the strength of, and fractional area covered by, magnetic fields (Leighton 1959). Wilson (1978) was the first to demonstrate that many solar-type stars exhibit long-term cyclic variations in their Ca II H and K (hereafter Ca HK) emission, analogous to the solar variations.

Significant progress in dynamo modeling emerged after helioseismology provided meaningful constraints on the Sun's interior structure and dynamics (Brown et al. 1989; Schou et al. 1998). Variations in the mean strength of the solar magnetic field lead to significant shifts ($\sim 0.5 \mu\text{Hz}$) in the frequencies of even the lowest-degree p-modes (Libbrecht & Woodard 1990; Salabert et al. 2004). Space-based asteroseismology missions, such as *MOST* (Walker et al. 2003), *CoRoT* (Baglin et al. 2006), and *Kepler* (Borucki et al. 2010), as well as ground-based net-

works like the Stellar Observations Network Group (SONG; Grundahl et al. 2008), are now allowing additional tests of dynamo models using other solar-type stars (e.g., see Chaplin et al. 2007; Metcalfe et al. 2007).

The F8V star ι Horologii (ι Hor \equiv HD 17051 \equiv HR 810, $V=5.4$, $B-V=0.57$) hosts a non-transiting $2 M_J$ exoplanet with an orbital period of 311 days (Kürster et al. 2000; Naef et al. 2001). Although it is currently situated in the southern hemisphere, kinematic considerations have led to the suggestion that it could be an evaporated member of the Hyades cluster (Montes et al. 2001). Asteroseismic observations support this conclusion, since the acoustic oscillation frequencies of the star are best reproduced with models that have the same metallicity, helium abundance, and stellar age as other Hyades members (Vauclair et al. 2008).

We report the discovery of a 1.6-year magnetic activity cycle in ι Hor from synoptic Ca HK measurements obtained with the Small and Moderate Aperture Research Telescope System (SMARTS) 1.5-m telescope at Cerro Tololo Inter-american Observatory (CTIO) since 2008. We provide an overview of the survey methodology and analysis methods in §2, and we present the stellar activity measurements and other derived properties in §3. We conclude with a discussion of the broader implications of this discovery for stellar dynamo modeling and future observations in §4.

2. OBSERVATIONS & DATA REDUCTION

The chromospheric activity survey of Henry et al. (1996) contained a total of 1016 observations of 815 individual stars with visual magnitudes between 0.0 and about 9.0, which were observed using the *RC Spec* instrument on the CTIO 1.5-m telescope. Several sub-samples were defined, including the “Best & Brightest” (B) and “Nearby” (N) samples, which together contain 92 individual stars with visual magnitudes between 0.0 and 7.9, and $B-V$ colors that are approximately solar. In August 2007, we began a long-term Ca HK monitoring program for the 57 stars in the combined (B+N) sample that are brighter than $V=6$ (Metcalfe et al. 2009), the limiting magnitude of future ground-based asteroseismic observations

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TABLE 1
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DATE	UT	HJD (2450000+)	S_{MWO}	σ_S	DATE	UT	HJD (2450000+)	S_{MWO}	σ_S
2008-02-15	01:18:19	4511.55234	0.2349	0.0023	2009-01-31	02:22:28	4862.59740	0.2625	0.0018
2008-02-15	01:19:33	4511.55319	0.2350	0.0022	2009-02-08	01:07:19	4870.54491	0.2716	0.0021
2008-03-16	23:49:03	4542.48971	0.2282	0.0014	2009-02-08	01:08:33	4870.54576	0.2676	0.0024
2008-03-16	23:50:17	4542.49056	0.2340	0.0014	2009-02-24	00:59:15	4886.53882	0.2658	0.0019
2008-07-09	09:06:28	4656.87999	0.2324	0.0022	2009-02-24	01:00:29	4886.53967	0.2634	0.0019
2008-07-09	09:07:42	4656.88085	0.2333	0.0023	2009-03-05	00:59:01	4895.53846	0.2647	0.0019
2008-07-25	09:32:42	4672.89890	0.2279	0.0016	2009-03-05	01:00:15	4895.53932	0.2667	0.0019
2008-07-25	09:33:56	4672.89975	0.2365	0.0017	2009-03-28	23:58:09	4919.49599	0.2747	0.0019
2008-07-27	08:52:52	4674.87132	0.2178	0.0016	2009-03-28	23:59:22	4919.49683	0.2721	0.0018
2008-07-27	08:54:05	4674.87216	0.2219	0.0017	2009-07-01	09:52:11	5013.91137	0.2738	0.0021
2008-08-03	10:02:01	4681.91961	0.2120	0.0012	2009-07-01	09:53:25	5013.91222	0.2762	0.0022
2008-08-03	10:03:15	4681.92046	0.2198	0.0012	2009-08-04	09:34:58	5047.90085	0.2563	0.0022
2008-08-18	09:32:47	4696.89982	0.2269	0.0014	2009-08-04	09:36:12	5047.90171	0.2566	0.0023
2008-08-18	09:34:01	4696.90067	0.2264	0.0014	2009-09-13	06:47:36	5087.78568	0.2349	0.0013
2008-09-07	05:12:15	4716.71937	0.2221	0.0013	2009-09-13	06:48:50	5087.78653	0.2326	0.0013
2008-09-07	05:13:28	4716.72022	0.2235	0.0013	2009-10-17	04:40:09	5121.69716	0.2334	0.0015
2008-09-15	06:05:01	4724.75613	0.2319	0.0015	2009-10-17	04:41:23	5121.69802	0.2326	0.0015
2008-09-15	06:06:15	4724.75699	0.2331	0.0015	2009-11-03	05:06:12	5138.71491	0.2232	0.0016
2008-09-25	04:50:18	4734.70432	0.2206	0.0012	2009-11-03	05:07:26	5138.71577	0.2281	0.0017
2008-09-25	04:51:31	4734.70516	0.2264	0.0013	2009-11-18	03:17:39	5153.63906	0.2269	0.0034
2008-10-04	05:20:31	4743.72530	0.2276	0.0013	2009-11-18	03:18:53	5153.63991	0.2202	0.0032
2008-10-04	05:21:45	4743.72616	0.2291	0.0014	2009-12-18	04:21:32	5183.68213	0.2204	0.0015
2008-10-12	05:16:34	4751.72251	0.2368	0.0027	2009-12-18	04:22:46	5183.68299	0.2212	0.0014
2008-10-12	05:17:48	4751.72336	0.2320	0.0028	2009-12-24	04:08:00	5189.67244	0.2131	0.0017
2008-10-25	05:56:51	4764.75028	0.2314	0.0015	2009-12-24	04:09:14	5189.67330	0.2134	0.0015
2008-10-25	05:58:05	4764.75114	0.2307	0.0015	2010-01-09	02:54:30	5205.62063	0.2190	0.0020
2008-11-02	06:32:48	4772.77507	0.2244	0.0015	2010-01-09	02:55:44	5205.62149	0.2112	0.0020
2008-11-02	06:34:02	4772.77592	0.2346	0.0016	2010-02-26	01:21:21	5253.55412	0.2271	0.0016
2008-11-10	05:11:55	4780.71867	0.2364	0.0015	2010-02-26	01:22:35	5253.55498	0.2288	0.0016
2008-11-10	05:13:09	4780.71953	0.2361	0.0015	2010-03-21	23:41:44	5277.48459	0.2260	0.0017
2008-11-26	06:04:01	4796.75427	0.2391	0.0015	2010-03-21	23:42:58	5277.48545	0.2186	0.0016
2008-11-26	06:05:14	4796.75510	0.2311	0.0014	2010-07-22	10:10:53	5399.92526	0.2542	0.0021
2008-12-02	04:04:26	4802.67098	0.2341	0.0017	2010-07-22	10:12:07	5399.92612	0.2488	0.0023
2008-12-02	04:05:40	4802.67183	0.2311	0.0016	2010-07-31	09:42:34	5408.90597	0.2513	0.0034
2009-01-13	02:57:40	4844.62263	0.2494	0.0015	2010-07-31	09:44:35	5408.90737	0.2515	0.0035
2009-01-13	02:58:54	4844.62349	0.2480	0.0015	2010-08-09	09:02:53	5417.87874	0.2389	0.0016
2009-01-31	02:21:14	4862.59654	0.2638	0.0018	2010-08-09	09:04:06	5417.87959	0.2468	0.0023

by SONG. All of the most promising southern asteroseismic targets are included in this B+N sub-sample.

Since January 2008, we have obtained 74 low-resolution ($R \sim 2500$) spectra of ι Hor covering 37 distinct epochs with the upgraded *RC Spec* instrument on the SMARTS 1.5-m telescope. Using standard IRAF⁵ routines, the 60 s integrations were subjected to the usual bias and flat field corrections and the spectra were extracted and wavelength calibrated using a reference He-Ar spectrum obtained immediately before the stellar exposures. Following Duncan et al. (1991), the calibrated spectra were then integrated in 1.09 Å triangular passbands centered on the cores of the Ca H and K lines and compared to 20 Å continuum passbands from the wings of the lines to generate a CTIO chromospheric activity index, S_{CTIO} . These values were converted to Mount Wilson indices (S_{MWO}) using data for 26 targets that were observed contemporaneously with the Solar-Stellar Spectrograph at Lowell Observatory (J. Hall, private communication), and adopting a quadratic function for the correlation (cf. Henry et al. 1996). The details of our observations of ι Hor are listed in Table 1. Note that the uncertainties shown in Table 1 represent only the internal errors. The systematic uncertainty from the conversion between the CTIO and MWO activity indices is $\sigma_{\text{sys}} \sim +0.007$ (MWO – CTIO).

⁵ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

In addition to the single-epoch observation from Henry et al. (1996), $S_{\text{MWO}} = 0.225 \pm 0.005$ on 1992.9479, there are several other Ca HK measurements of ι Hor in the literature that we can use to probe activity variations on longer timescales. Jenkins et al. (2006) published a recalibration of measurements originally made by Tinney et al. (2002) on 2001.5918 with $S_{\text{MWO}} = 0.249 \pm 0.002$. Gray et al. (2006) obtained a spectrum on 2002.9538 with a revised $S_{\text{MWO}} = 0.226 \pm 0.01$ (R. Gray, private communication). Finally, Schröder et al. (2009) measured $S_{\text{MWO}} = 0.246 \pm 0.03$ from a spectrum obtained on 2003.9387. Additional Ca HK measurements of ι Hor have appeared in the literature, but without sufficient detail to determine the precise epoch of the observation and the S index on the Mount Wilson scale.

3. RESULTS

Our time-series measurements of the Mount Wilson S index for ι Hor are plotted in Figure 1. We fit a sinusoid to these data and found a cycle period of $P_{\text{cyc}} = 1.6$ years around a mean value of $\langle S \rangle = 0.242$. The variations are not expected to be strictly sinusoidal, so the fitted amplitude of $A_{\text{cyc}} = 0.024$ does not capture the full range of observed values from $S \sim 0.21$ – 0.28 , nearly 30% of the mean activity level (the solar range is $S \sim 0.17$ – 0.20 ; Baliunas et al. 1995). The parameter values of the fit do not change significantly when including the few archival data points, and all but the Gray et al. measurement agree with the extrapolated sinusoid at the 1σ level.

We were initially intrigued that the activity maximum at

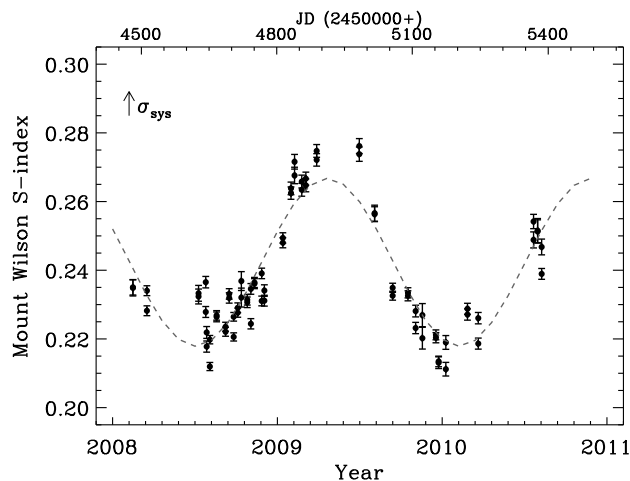


FIG. 1.— Chromospheric activity measurements of the F8V star ι Hor from the southern HK survey (Metcalf et al. 2009), showing a clear variation with a cycle period of 1.6 years, the shortest cycle measured for a sun-like star. Note that the error bars represent only the measurement errors, and do not include the systematic uncertainty $\sigma_{\text{sys}} \sim 0.007$ (arrow).

2009.3 coincided with an epoch of periastron for the eccentric exoplanet in the system (cf. Naef et al. 2001). Although activity induced by hot Jupiters has been seen in a few cases (e.g., see Walker et al. 2008), we would not expect it in this case because even at periastron the star-planet separation is 0.7 AU. The exoplanet orbital period of 311 days bears no obvious relation to the cycle period of 584 days, so this appears to be simply a coincidence.

Asteroseismic observations of ι Hor by Vauclair et al. (2008) in 2006.9 coincided with the magnetic minimum one cycle prior to the beginning of our data set. As first observed in the Sun more than two decades ago (Libbrecht & Woodard 1990), the global oscillation frequencies are shifted significantly from solar minimum to maximum. The amplitude of these frequency shifts was predicted to be larger ($\sim 1 \mu\text{Hz}$) for stars hotter than the Sun (see Metcalfe et al. 2007; Karoff et al. 2009), as was recently confirmed in the F5V star HD 49933 by García et al. (2010). Future asteroseismic observations near the magnetic maxima that coincide with the observing season for ι Hor in late 2010 or 2013 have the best chance of detecting these frequency shifts.

The scatter around the sinusoidal variation in Figure 1 is caused in part by rotational modulation of individual active regions. Based on prior single-epoch measurements of its chromospheric activity level, the rotation period of ι Hor was estimated to be 7.9 days (Saar & Osten 1997). After normalizing our measurements by the 1.6 year sinusoid, we passed the residuals through a Lomb-Scargle periodogram (Lomb 1976; Scargle 1982) to search for the signature of rotation. The results are shown in Figure 2, with the highest peak at $P_{\text{rot}} = 8.5 \pm 0.1$ days and a smaller peak near 7.9 days. We verified that a single sinusoid with a period of 8 days, sampled in the same way as our data, produces a clear and significant peak in the periodogram. Of course, the rotational modulation of individual active regions will not be coherent over the span of our data set, and spots at different latitudes may have different periods. These effects will tend to reduce the significance of individual peaks in the periodogram. However, a recent analysis by Boisse et al. (2010) of the radial velocity measurements from Vauclair et al. (2008) found evidence of rotation in ι Hor with periods in the range 7.9 to 8.4 days, con-

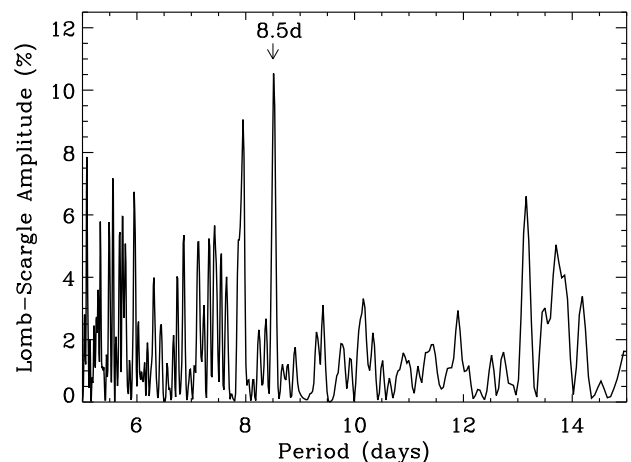


FIG. 2.— The Lomb-Scargle periodogram of our Ca HK measurements after removing the 1.6 year sinusoid, suggesting a rotation period that is consistent with Hyades membership for this star.

sistent with the dominant peaks in Figure 2 from our Ca HK measurements. The mean rotation period of solar-type stars in the Hyades is ~ 8.4 days (Radick et al. 1995), so both of these results support the conclusions of Montes et al. (2001) and Vauclair et al. (2008) that ι Hor is an evaporated member of the cluster.

If we combine the asteroseismic radius of ι Hor, $R = 1.18 R_{\odot}$ (S. Vauclair, private communication) and the rotation period above with the measured $v \sin i = 6.47 \pm 0.5 \text{ km s}^{-1}$ from Butler et al. (2006), we can obtain an estimate of the inclination angle, $i \sim 60^{\circ}$. If the rotation axis is perpendicular to the orbital plane of the exoplanet⁶, then the absolute mass of the planet is only about 15% larger than the minimum mass obtained from the radial velocity orbital solution.

4. CONCLUSIONS & DISCUSSION

The immediate question that arises from the observation of such a short activity cycle is whether we can understand it in the context of dynamo models that are frequently invoked to explain the 11-year solar cycle. It is generally difficult to extrapolate solar dynamo models to other stars because it is not well understood how the underlying parametrizations change for different stellar properties. However, in the case of ι Hor we can take advantage of a lucky coincidence—an F8 star with a rotation period near 8 days has a Coriolis number $2\Omega\tau_c$ that is very similar to that of the Sun (Küker & Rüdiger 2005). Since the Coriolis number characterizes the influence of rotation on convection, it determines to a large extent the overall direction and profile of the turbulent Reynolds stresses (RS) that drive differential rotation and meridional flow. The amplitudes are expected to be different due to the higher luminosity and resulting convective velocities ($\text{RS} \sim v_c^2$), but it still allows us to make some simple estimates of how various dynamo scenarios considered for the Sun are expected to scale to ι Hor.

From a standard stellar evolution model of ι Hor with the global properties inferred from asteroseismology (Vauclair et al. 2008), we deduce that the convective velocity v_c is 2.8 times higher than the solar value while the relevant

⁶ Note that recent measurements of the Rossiter-McLaughlin effect for some transiting hot Jupiter systems suggest a substantial spin-orbit misalignment (e.g., see Schlaufman 2010).

timescale τ_c is 3.2 times shorter (due to a smaller pressure scale height). Using simple scaling relations these quantities allow us to estimate turbulent diffusivities η_t , ν_t that are 2.4 times solar. The meridional flow speed v_m is expected to be about 2.6 times solar (from angular momentum transport balance, $v_c^2 \sim v_m \Omega$) and the differential rotation 2-3.3 times solar (considering thermal balance $\Omega \Delta \Omega \sim \Delta T$ and angular momentum transport balance $v_c^2 \sim \nu_t \Delta \Omega$). Additional scaling factors of order unity can arise from the different depth and aspect ratio of the convection zone. Nevertheless these estimates agree very well with the differential rotation model for an F8 star presented in Küker & Rüdiger (2005).

The above properties would lead us to predict a cycle period of 4-5 years for an advection dominated flux-transport dynamo ($P_{\text{cyc}} \sim v_m^{-1}$), or 3.5-5 years for a classical α - Ω dynamo ($P_{\text{cyc}} \sim [\Delta \Omega \alpha]^{-0.5}$, assuming $\alpha \sim v_c$). These estimates are both more than a factor of two longer than the observed cycle, but for the flux transport dynamo we assumed that the underlying conveyor belt would extend to similar latitudes as observed in the Sun. Due to the larger aspect ratio of the convection zone in an F8 star as well as the larger magnetic diffusivity, it is conceivable that the flux transport is cut short leading to a significant reduction in the dynamo period. Currently, B. P. Brown et al. (in preparation) are exploring dynamo action in solar-type stars rotating at 3-5 times the solar rate using global 3D anelastic MHD models. For a sufficiently large level of turbulence, cyclic behavior is found with periods of a few years or less. These studies demonstrate that computing a detailed 3D model of ι Hor should already be possible.

Prior to the discovery of this 1.6-year magnetic cycle in ι Hor, the shortest measured cycle periods were 2.52 years (HD 76151) and 2.60 years (HD 190406) from the Mount Wilson survey (Baliunas et al. 1995). Both of these appeared to be secondary cycles superimposed on a much longer primary cycle. Böhm-Vitense (2007) has suggested, based on the sample of stars with well characterized rotation and cycle periods in Saar & Brandenburg (1999), that the “active” and “inactive” branches in the P_{rot} - P_{cyc} diagram may be caused by two distinct dynamos that are driven in different regions of the star. Specifically, Böhm-Vitense suggests that the active branch may represent a dynamo operating in the near surface shear layer, while the inactive branch is driven by the shear layer at the base of the convection zone. In this scenario, stars that exhibit cycle periods on both branches must have the two types of dynamos operating simultaneously. If the 1.6-year cycle in ι Hor is on the inactive branch, then the active branch cycle period is expected to be near 6 years. Although the previous Ca HK measurements are sparse, we see no evidence of a secular trend in S_{MWO} on longer timescales. Continued observations by our program should yield stronger constraints on possible slow variations.

Recently, García et al. (2010) detected the signature of a short magnetic activity cycle in the F5V star HD 49933 using asteroseismic measurements from the CoRoT satellite (Appourchaux et al. 2008; Benomar et al. 2009). Just as in the Sun, where the global oscillation modes shift to higher frequencies and lower amplitudes towards the maximum of the 11-year solar cycle, HD 49933 appeared to pass through a magnetic minimum during 137 days of continuous observations. An additional 60 days of data from an earlier epoch could not place strong constraints on the cycle period, but

suggested a value between 120 days and about 1 year. If confirmed by ground-based monitoring of the Ca HK lines, this would place HD 49933 (with $P_{\text{rot}} = 3.4$ d) in the same category of magnetic cycle observed in ι Hor.

The asteroseismic signature of a short magnetic cycle has also been detected in the Sun itself. Fletcher et al. (2010) analyzed the low-degree solar oscillation frequencies from the BiSON and GOLF experiments and found evidence of a quasi-biennial (2 year) signal in both data sets after removing the dominant 11-year period. Unlike the 11-year signal, the amplitude of the 2-year variation appeared to be largely independent of frequency, leading the authors to suggest that the secondary cycle must be operating independently. However, the amplitude of the 2-year signal was uniformly larger during the maximum of the 11-year cycle, suggesting that buoyant magnetic flux might be rising from the base of the convection zone and pumping up a near-surface dynamo with the 2-year period. Active branch stars with a cycle period of 11 years are expected to show a secondary cycle period on the inactive branch around 2 years. However, this normally occurs in stars rotating at twice the solar rate, and the identification of the two dynamos would then be reversed—with the 11-year dynamo operating in the near-surface shear layer, while the 2-year dynamo is driven at the base of the convection zone.

If short magnetic activity cycles are common, NASA’s *Kepler* mission should detect them in the asteroseismic measurements of many additional stars. In principle such measurements can provide unique constraints on the underlying physical mechanism, and *Kepler* will also yield measurements of some of the key dynamo ingredients. Even without the short cadence data for asteroseismology, the high precision time-series photometry from *Kepler* is sufficient to characterize the surface differential rotation through detailed spot modeling (e.g., see Basri et al. 2010). For the brighter asteroseismic targets where the individual oscillation frequencies are detectable, the time series will be long enough to resolve rotational splitting of the modes into multiplets for stars with rotation rates between about 2 and 10 times the solar rate (Ballot et al. 2008). Measurements of the rotational splitting as a function of radial order can indirectly probe radial differential rotation, since the various modes sample slightly different (but overlapping) regions of the star. For the very best and brightest asteroseismic targets, *Kepler* will obtain a frequency precision sufficient to measure the depth of the surface convection zone from the oscillatory signal in the so-called second frequency differences (e.g., see Verner et al. 2006). The *Kepler* mission is expected to document all of these properties in at least a few dozen solar-type stars, gradually leading to a broader context for our understanding of the solar dynamo.

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